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**PIONEER VENUS ORBITER
Report of a Study by the
NASA/ESRO Joint Working Group - January 1973**

**Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035**

August 1974

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NASA/ESRO JOINT WORKING GROUP

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CONTENTS

	Page
Chapter 1 INTRODUCTION	1
Chapter 2 MISSION SUMMARY	2
Chapter 3 SPACECRAFT DESCRIPTION	4
General Features	4
Launch Vehicle	4
Rocket Motor and Propellant	4
Structural Design	4
Chapter 4 CANDIDATE PAYLOADS	7
General Considerations	7
Plasma and Magnetic Field Measurements	10
Photoelectron/Solar Wind Analyzer	11
Electron and Ion Temperature Measurements	11
Neutral and Ion Mass Spectrometers	12
Ultraviolet Spectroscopy	13
Infrared Radiometry	14
Radar Altimetry	15
Radio Occultation Measurements	17
Gravitational Measurements	18
Supporting Studies	20
Conclusions	20

Chapter 1

INTRODUCTION

This report is a sequel to two earlier ones devoted to the Pioneer Venus program. The first report,¹ completed in 1970, outlined the philosophy and justification for exploration of Venus by a series of small probes, orbiters, and landers. The second,² published in 1972, was devoted to a detailed study of the multiple-probe mission, and a preliminary study of an orbiter.

The Orbiter mission is the subject of the present document. In accordance with the low-cost Pioneer Venus concept discussed in the earlier reports, NASA intends to use the same basic spacecraft, known as the "bus," for the execution of the two missions. The bus will be equipped with all of the subsystems common to the Probe and Orbiter missions (for example, thermal control, solar cells and power supply, attitude measurement and control, telemetry and communication electronics, and auxiliary propulsion unit). For the 1977 mission, the bus will be equipped with the large and small probes and a special antenna system. For the Orbiter mission, the bus will be equipped with a retro-propulsion motor and a high-gain antenna. A diagram of the system envisaged is shown in Chapter 3, Figure 1.

At a meeting in April 1972, attended by members of NASA and the European Space Research Organization (ESRO), it was decided to examine jointly the terms on which both organizations could cooperate in the execution of the Venus Orbiter mission in 1978. The principles of such cooperation, which will not involve any exchange of funds between the two organizations, can be summarized as follows:

- NASA will produce and provide ESRO with the Orbiter version of the basic spacecraft (the "bus") together with the common equipment.
- ESRO will adapt the bus as appropriate, add the equipment specific to the Orbiter mission (in particular the retromotor and high-gain antenna), and carry out the integration of the scientific experiments as well as the qualification tests. Experiment proposals from both U.S. and European scientists will be considered.
- The Orbiter will then be delivered to NASA, which will be responsible for the launching and flight operations.

The present NASA/ESPO Pioneer Venus Orbiter report gives the main outcome of the meetings held by a Joint Working Group, which was set up to define the objectives of a Venus Orbiter for launch in 1978. The proposed candidate payload is based on the current results of technical studies conducted by Ames Research Center, ESRO, and their contractors.

¹ Venus: Strategy for Exploration. Space Science Board, National Academy of Sciences, 1970.

² Pioneer Venus: Report of a Study by the Science Steering Group. Ames Research Center, June 1972.

Chapter 2

MISSION SUMMARY

In response to the desire on the part of the scientific community to explore the planet Venus, the National Aeronautics and Space Administration (NASA) has established the Pioneer Venus program. The Pioneer Venus Study Team, located at NASA Ames Research Center, is currently directing the program Phase B or System Definition Phase effort with two major system contracts. Two American aerospace teams have been formed to competitively define the Pioneer Venus spacecraft system. They are TRW/Martin Marietta and Hughes/General Electric. One of these teams will be selected to perform the Execution Phase of the program.

In parallel with these activities and based on agreements established between NASA and the European Space Research Organization (ESRO), an ESRO Venus Orbiter Study Team has been formed with the system definition activity contracted to Messerschmitt-Bolkow-Blohm (MBB), Munich, West Germany. Close technical and management coordination has been established between NASA and ESRO with specific agreements and interfaces to be defined following the Phase B activity (mid-year 1973).

Since the inception of the NASA Venus exploration concept, a series of missions has been proposed. A series combining the capabilities of Orbiters and Probes to the planetary surface would provide the ideal method of exploring the environment of Venus. In mid-1972, the present mission series was defined. This mission series calls for a Multiprobe mission in the 1976/1977 launch opportunity with an Orbiter mission in 1978. The science requirements for this mission series have been documented in the Pioneer Venus report referenced above (see page 1 footnote 2). The science requirements for the Orbiter mission have been updated in this document.

Based on the recommendations of the Pioneer Venus Science Steering Group (January - June 1972) and the Pioneer Venus Orbiter NASA/ESRO Joint Working Group (September 1972 - January 1973), and the program schedule requirements for the implementation of the Execution Phase, the following launch opportunities have been selected for design of the two mission series:

(a) Multiprobe Mission

Launch	1/5/77 - 1/14/77
Arrival	5/16/77

(b) Orbiter Mission (Type 1)

Launch	8/24/78 - 9/3/78
Arrival	12/15/78 - 12/20/78

Orbiter Mission (Type II)

Launch	5/25/78 - 6/3/78
Arrival	12/10/78 - 12/12/78

NOTE

These dates are based on present (January 1973) mission analysis results and therefore do not represent final mission planning.

The science requirements for the Orbiter mission indicate a preference for a highly inclined orbit plane, e.g., greater than 60° (referred to ecliptic) to near polar; for a low periapsis, e.g., 200 km or less; for a mid-latitude periapsis location, e.g., near 45° ; and for the periapsis location to initially exist in sunlight for a period of time prior to crossing the terminator into darkness. The operation in orbit should allow investigation over at least one sidereal year (225 Earth days) and preferably one Venus rotation period (243 days).

A typical mission sequence can therefore be presented as it is related to the planetary orbital characteristics using the science requirements as a baseline. Following two or three midcourse maneuvers, the spacecraft will be targeted to a point at the planet where an on-board retromotor can apply the proper change in velocity (ΔV). An attitude maneuver will position the spacecraft spin axis for application of the correct ΔV by the retromotor at Venus orbit insertion. An initial periapsis altitude may be between 400 and 700 km with later orbital change maneuvers to lower this altitude to approximately 150 to 200 km. Apoapsis altitude may be 60,000 to 70,000 km. A 24-hour orbital period will result. With most of the aforementioned science requirements satisfied. The primary operating region for a typical science payload (as described in this document) will be while the spacecraft passes below an altitude of 5000 km, as it approaches periapsis, and again rises to an altitude of 5000 km on each planet orbit. Therefore, scientific interest will increase as the altitude decreases to periapsis and vice versa following the rise from periapsis on each orbit.

Solar gravity effects on the periapsis altitude will cause it to rise or fall, depending on selected periapsis location. Periodic orbital change maneuvers will be required to maintain a designated range of periapsis altitude (150 to 200 km).

A desire has been indicated for survival of the mission beyond the nominal 225 days, particularly for gravity harmonic measurements.

Chapter 3

SPACECRAFT DESCRIPTION

GENERAL FEATURES

The Pioneer Venus Orbiter will be a mission-adapted version of the Probe/Bus spacecraft. The Orbiter will be spin-stabilized and solar-powered, and will carry a science payload of 25 to 36 kg (55 to 80 lb).

The final spacecraft design has not yet been selected. An important question, so far unresolved, is the orientation of the spin axis; the choice is between one which is normal to the ecliptic plane, and one which is in the ecliptic plane, pointed at Earth. Both designs have been shown to be feasible, and both offer comparable system capability. Detailed work is now under way to further examine the advantages and disadvantages of each, particularly the coverage afforded to planetary science. Relative design complexities, subsystem performance limitations, and overall system costs are additional major considerations.

LAUNCH VEHICLE

The mission is based on the capability of the Delta 2914 launch vehicle. Total spacecraft weight at launch in 1978 would be approximately 365 kg (800 lb). The weight in orbit (periapse 200 km, apoapse 65,000 km, period 24 hr) would be approximately 180 kg (400 lb). It is possible that an Atlas/Centaur will be used instead of the Delta, to permit a relaxation of some weight restrictions, only if a reduction of total cost can be achieved. The capability of the spacecraft and experiments will, however, not be permitted to grow.

ROCKET MOTOR AND PROPELLANT

The Orbiter spacecraft will require a retro-propulsion maneuver at Venus to achieve orbit injection. The magnitude of the ΔV required is approximately 1600 m/sec for a Type I transfer trajectory, and approximately 950 m/sec for a Type II transfer. The insertion may be accomplished by use of a solid propellant rocket motor. A number of existing motors have been identified which cover the combinations of spacecraft mass and orbits of interest. The use of a liquid propellant motor system is also being investigated; it offers the advantage that the amount of propellant carried can readily be changed as required from mission to mission.

STRUCTURAL DESIGN

The final Pioneer Venus Orbiter configuration and structural design will be highly dependent on the major system decisions discussed above. Pending those decisions, only a general description and definition can be given.

The spacecraft will typically be a short cylinder of large diameter. The Delta shroud can accommodate spacecraft diameters up to 213 cm (84 in), while the maximum diameter for Atlas/Centaur is approximately 256 cm (101 in). The final design configuration will probably be near these launch vehicle envelope limits. In adapting from the Probe/Bus to the Orbiter configuration, the probe-supporting structure would be removed and replaced with supports for the high-gain antenna. Basic structural elements would be common to both configurations. (Refer to Figure 1.)

The Pioneer Venus Orbiter will be powered by solar cells with provision for secondary battery power during periods of solar occultation. The present power budget provides approximately 40 watts (continuous) for science instruments.

Earth-spacecraft communications will be via the NASA Deep Space Network. The 26-meter antennas will be the primary ground station facility. The 64-meter antennas will also be employed; however, this support would be limited to periods of critical maneuvers and vital data collection. Spacecraft telemetry and command links will be at S-band. Telemetry bit rates during the mission will range between 2000 bps and 100 bps, depending on link distance and final design selections in the communication subsystem. The Earth-pointed design would use a fixed parabolic dish antenna on axis, while the normal-to-ecliptic system would require some form of despun antenna.

The spacecraft telemetry system will be capable of providing a variety of data formats, selectable by command, to accommodate particular science and engineering requirements. The spacecraft data handling system will include data storage sufficient to preserve science data collected during Earth occultation, and to buffer data collected over brief periods at rates higher than telemetry transmission.

Spacecraft attitude will be stabilized by spinning at a rate of approximately 5 rpm. Attitude maneuvers, trajectory corrections, and orbit-trim maneuvers will be performed with an array of small hydrazine monopropellant thrusters. On-board fuel capacities will be sufficient to maintain the orbit for the entire 243-day mission.

The spacecraft structure will provide for the mounting of science instruments on a common, thermally-controlled platform. Radial, forward or aft instrument-viewing requirements will be accommodated.

Magnetic cleanliness criteria have not yet been specified. Guidelines for the system studies have emphasized the need to define these criteria with full consciousness of the total cost. The present indications are that a reasonable program can be implemented which would limit both permanent and stray field levels to less than 10 γ at a distance from the spacecraft of approximately 3 m.

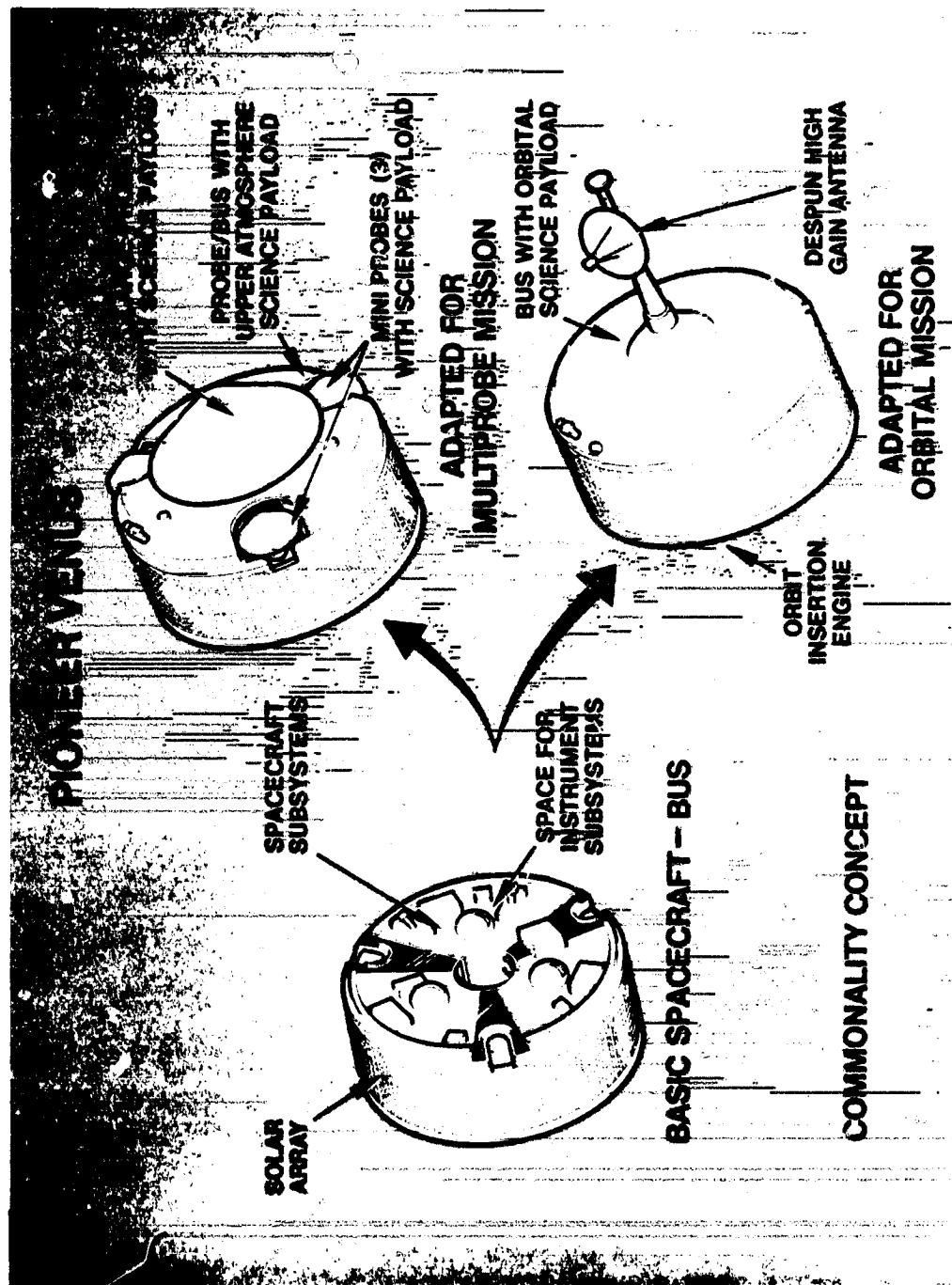


Figure 1

Chapter 4

CANDIDATE PAYLOADS

GENERAL CONSIDERATIONS

The principal objectives of the Orbiter mission, already stated in the Pioneer Venus Science Steering Group (SSG) report, have been reasserted by the NASA/ESRO Joint Working Group (JWG):

(1) Global mapping of the atmosphere and the ionosphere by remote sensing and radio occultation to extend the information obtained on the vertical structure from the entry probe mission.

(2) Global studies by in situ measurements of the upper atmosphere, ionosphere, and solar wind-ionosphere interaction region to extend and supplement the information obtained with the entry probe mission.

(3) Studies of the planetary surface by remote sensing.

In order to establish a typical payload that would be well suited to achieve these scientific objectives, the JWG discussed a number of candidate experiments, using recommendations given in the SSG report, plus additional results currently available from studies by Ames Research Center (ARC) and the European Space Research Organization (ESRO).

Selection Criteria

Each candidate experiment is discussed in detail below. Basic considerations for the selection were as follows:

- To include, as much as possible, only flight-tested or well-proven instrumentation.
- To give priority to instruments which will achieve scientific objectives not accessible by the Probe mission.
- To weigh the advantages and interest of each instrument against the complexity it will involve in the spacecraft itself.
- To consider mainly experiments that are compatible with a rather long orbital period (24 to 48 hours) and a low periapsis altitude (~200 km).

Payload A

In Table 1, a model payload is listed (Payload A). It assumes that 36.5 kw will be available for the scientific payload (including booms and special antennae). This is considered to be reasonable, if the required power is not more than 30 w and the majority of experiments will not be operated during eclipses.

Table 1. Venus Orbiter Model Payload (Payload A)

Experiment	Instrument	Weight (kg)	Power (w)	Data (bps) (nominal)
Solar wind/ionosphere interaction	Magnetometer ¹	3.5	2	32
	Solar wind and photo-electron analyzer	2.5	2	36
	Electron and ion temperature probe	2.0	3	25
Aeronomy (composition, photochemistry, airglow)	Neutral mass spectrometer	4.0	10	100
	Ion mass spectrometer	1.5	1	100
	UV spectrometer/photometer	6.0	4	≤600
Atmosphere (thermal structure, lower atmosphere density)	IR radiometer	5.0	4 ⁴	150
	Dual frequency occultation (add. X-band) ²	3.0	10	-
Surface (topography, reflectivity, roughness)	Radar altimeter ³	9.0	11	300
		36.5	~30 ⁵ (Avail.)	128 ⁵ (At max. distance)
¹ Including 2- to 3-m boom. ² Associated with the telecommunication subsystem (S-band). ³ A dedicated antenna is preferred to one shared with the communications system. ⁴ Must be 14 w if a horizon scanner is used. ⁵ To satisfy payload requirements on power and data rates, a proper duty cycle will be necessary.				

Payload B

In the event that only a reduced payload is feasible (30 kg), the JWG made the following recommendations (Payload B):

- Simplify the solar wind/ionosphere interaction complex.
- Simplify the UV instrument (H/D ratio measurement considered imperative).
- Abandon ionic temperature measurement with the dedicated analyzer.

Payload C

In the event that a radar altimeter is not feasible within the 9 to 10 kg weight limit, it will be necessary to revise the payload. The JWG made the following recommendations (Payload C):

- Improve the dual frequency occultation experiment (X band and/or L-band).
- Improve the orbit (shorter period, more trim maneuvers, etc.)
- Relax weight constraints on some experiments.

Additional Experiments

A number of other experiments were considered by the JWG but were not retained in the candidate payloads. The principal ones were:

- A microwave radiometer aiming at a resolution of $\pm 1^\circ\text{K}$ for mapping the thermal emission of the surface.
- An ac electric field sensor to detect plasma waves originating from the solar wind/ionosphere interaction.
- A solar UV occultation experiment to determine the vertical distribution of minor constituents in the upper atmosphere of Venus.
- A photopolarimeter (UV, visible, IR) was also included.

Other Considerations

The JWG emphasized the importance of using the Orbiter mission for Venus gravimetry through analysis of long-period perturbations. However, this would be difficult to achieve with low periapsis requirements and orbital maneuvers. Extension of the Orbiter beyond the nominal lifetime could be requested in order to achieve accurate gravimetry.

Finally, it is recommended that during Sun occultation occurring at the end of the nominal mission (243 days), full benefit of the dual-frequency experiments be exploited in order to conduct time delay measurements for testing general relativity.

PLASMA AND MAGNETIC FIELD MEASUREMENTS

Observations of the plasma and magnetic field environments of Venus are considered to be of prime importance as far as an Orbiter mission is concerned for the following reasons:

(1) We do not at this point know whether or not Venus has a small magnetic field of internal origin.

(2) The ionopause and plasma tail observed during the flyby of Mariner 5 are probably the most intriguing results that have been obtained to date.

(3) For planets such as Venus which have at most a weak internal magnetic field, the solar wind interaction determines the upper boundary condition on the atmosphere, and hence controls the evolution of the atmosphere to a large extent.

Present knowledge of solar-wind interaction with the upper atmosphere of Venus indicates that the planet has no internal magnetic field. However, one cannot be definite about this point. Since the magnetic field may play an important role in determining solar wind interaction and hence the evolution of the atmosphere, it is important that careful magnetic field measurements be made from the Orbiter. It should also be noted that these are probably the only active measurements which will provide information concerning the interior of the planet.

The sharply bounded ionopause on the sunward side of Venus and the extended plasma tail on the downstream side found by Mariner 5 were quite unexpected features; at this time, they are still not adequately explained or understood. Consequently, the plasma and magnetic field experiments should be designed so that they can provide an adequate answer to all questions that arise in connection with these phenomena. In particular, it is necessary to be able to measure the bulk properties of the solar wind (density, temperature, pressure, speed and direction), the strength and direction of the magnetic field (to an accuracy of 0.1 to 0.5 gammas), and the density, temperature, composition and possibly the flow of the ionospheric plasma. At the same time the experiments must not be allowed to become too complex in order that the payload can have a proper scientific balance. In particular, care must be taken to avoid making excessive demands for magnetic cleanliness, and it will probably be necessary to omit detailed measurements of the ion composition of the solar-wind plasma if these cannot be done without a significant penalty in terms of the spacecraft capability.

Since the average interplanetary magnetic-field strength at the orbit of Venus is of the order of 10 gammas, and the Orbiter will not normally be in regions with fields much lower than this (except possibly in the plasma tail, and at times when the interplanetary field strength is unusually low), a highly sensitive magnetometer system is not required. Furthermore, since this is intended to be a low-cost mission, it is inappropriate to request an extensive program to ensure that the spacecraft is magnetically clean, and in any case, such costs will be charged directly to the magnetometer experiment. It is suggested, in fact, that the magnetic cleanliness program be restricted to

one of simply recommending guidelines to other experimenters. Consideration should therefore be given to mounting the magnetometer on a boom, and use of (a) the gradiometer technique for determining at least the dipole component of the spacecraft field and/or (b) the various techniques involving the properties of fluctuations in the interplanetary field, which permit the zero level of the magnetometer to be inferred. It appears that the use of a 3-meter boom will permit the field at the sensor to be reduced to 0.5 gammas without special cleaning of the spacecraft. Taking into account the advantage associated with a spinning spacecraft, it should be possible to obtain the required sensitivity quite easily without embarking upon a costly magnetic cleanliness program.

PHOTOELECTRON/SOLAR WIND ANALYZER

The role of photoelectrons in the thermal balance of the Venusian ionosphere is difficult to predict without information about the configuration of the ionospheric magnetic field. In the complete absence of such a field, photoelectrons would be free to move through the ionosphere with a large, general, anti-solar flow into the nightside or plasma tail region. This flow of low-energy electrons would redistribute the dayside heat input and affect the electron-temperature profile. In contrast, if a magnetic field is present, lateral heat loss at lower altitudes would be smaller and higher dayside electron temperatures would result. The photoelectrons may also play an important role in the formation of the ionopause by their contribution to the total pressure balance.

Instruments capable of measuring both electron and proton fluxes in an energy range of about 10 ev to 30 kev have already been flown on a number of satellites and are planned for future programs. It appears highly desirable to use such an instrument for the Venus Orbiter. An instrument with sufficient sensitivity, energy resolution, etc., to measure both solar wind and photoelectron fluxes is feasible for the weight indicated in the candidate payload. Some compromises will have to be made in order to accommodate various requirements, but the scientific integrity of the measurements will not have to be sacrificed. A spin axis perpendicular to the ecliptic plane is desirable for this experiment. Good altitude coverage for the photoelectron measurements requires a low periapsis altitude.

ELECTRON AND ION TEMPERATURE MEASUREMENTS

The existence of the dayside ionopause (when considered in conjunction with Mariner 5 solar-wind data) suggests that a pressure balance exists between the solar wind streaming around the planet and the ionosphere just below the ionopause. A pressure balance implies high ionospheric plasma temperatures, $(T_e + T_i)/2$. Such an implication, however, depends upon many unproven assumptions about ion flow, induced fields, and currents in the Venusian upper ionosphere.

A measurement of the plasma temperature as a function of altitude on the dayside of Venus would help determine which of several reasonable models of the upper ionosphere is possible. A high value of T_e would imply a nearly impermeable barrier between solar wind particles and the dayside ionosphere, while a low value would imply a turbulent ionopause with a significant fraction of the solar-wind particles leaking into the ionosphere. If the ionopause does permit solar-wind electrons and protons to pass into the ionosphere, then even a small percentage penetration would provide an important heat source and a sufficient ionization source to maintain the nightside ionosphere.

Vertical profiles of electron and ion temperatures (when combined with neutral-composition and scale-height data) can be used to determine ionospheric heating rates. Electron and ion temperature probes have been flown successfully on many satellites during the last decade. The best measurements have been obtained when separate sensors were used. Satellite-borne ion traps have also provided useful ion composition data; therefore, this instrument is useful as a backup to the ion mass spectrometer. Due to the lack of orientation of the satellite spin axis with respect to the velocity vector, a spherical ion sensor appears to be preferable, while either a cylindrical or spherical sensor would be appropriate for the electron probe. A mid-latitude periapsis position and a high inclination orbit are desirable for the experiment; low periapsis altitude (~200 km) would also be highly desirable. The choice of the spin axis orientation with respect to the ecliptic has no major impact on this instrument.

NEUTRAL AND ION MASS SPECTROMETERS

Mass spectrometry is an established and powerful tool for the investigation in situ of the Earth's upper atmosphere. There are problems in measuring neutral atomic species, due to chemical loss, and also production, in the ion source; but most of these problems are understood and can be handled. Dayglow and fluorescence experiments can be very helpful in checking the results. Spectrometry of ambient ions has extremely high sensitivity, and is an essential tool for the understanding of ionospheric physics. The neutral and ion composition, measured from a Venus C.biter, are basic to a knowledge of the upper atmosphere and its chemistry, both ion and neutral. Temperatures can be obtained from the gradients of selected species.

In addition, ion measurements during passages through the boundary of the solar wind will give important information complementary to that from the plasma and magnetic instruments.

It is possible to make alternate measurements of neutral and ionized species with the same instrument. The result, however, is a compromise, and the saving of weight and power is very small -- existing ion spectrometers weigh 1.5 kg and use 1 watt. With separate instruments, the ion source for neutral species can be optimized, probably with a closed geometry, to give precise densities. Such an instrument can weigh as little as 3 kg and use only 8 watts. For both instruments, the ideal mounting is normal to the spin axis, if the latter is nearly normal to the velocity vector near periapse. Other geometries are possible for other situations.

ULTRAVIOLET SPECTROSCOPY

The capability of an ultraviolet spectrometer for studying the upper part of a CO₂ atmosphere is best illustrated by the results from Mariners 6, 7, and 9. The spectra have been used to obtain, for Mars:

- The scale height of the CO₂ in the atmosphere, and thus the exospheric temperature.
- A description of the ionospheric structure and energetics.
- Estimates of the (surprisingly small) amounts of CO and O.
- Measurement of atomic hydrogen concentration and escape rate.
- Upper limits on other gases, especially nitrogen.
- Discovery of ozone in winter at medium and high latitudes.
- Mapping of the brightness, and therefore the depth, of the lower atmosphere.

On Venus, where the surface cannot be seen, additional information on the stratosphere and clouds may be expected. Dusky markings in the near ultraviolet can be observed from Earth, and close-up mapping of them could be of interest. Mariner 5 (and several sounding rockets) have observed the extensive Lyman-alpha corona due to H atoms, and conflicting evidence for D atoms as well. This question has a strong bearing on atmospheric evolution. It can be studied to some extent by the radial dependence of the Lyman alpha, but a much better technique, well tested in Earth orbit, is the use of resonance cells to separate the radiation from the two isotopes.

The Venus Orbiter as currently visualized will carry instruments -- notably mass spectrometers -- for measurements *in situ* near periapse. Thus, the UV measurements must complement, rather than duplicate, the direct ones. They permit observation to much lower altitudes, and also in geographical regions that are remote from periapse. Diurnal variations in the upper atmosphere are of great interest, because of the very slow rotation of Venus. Moreover, if the 4-day rotation of the cloud tops is like that of a solid body, the same rotation should exist at all greater heights. A channel of the UV instrument could well be devoted to mapping the dusky markings to elucidate the nature of the 4-day motion.

At still greater heights, there is a chance that UV spectroscopy will give evidence on the nature of the interaction of solar wind and ionosphere.

Two major classes of UV spectrometer are available: a scanning instrument, as used for Mars, weighing about 5 kg, and a concave-grating instrument with several fixed detectors, as used on Mariner Venus-Mercury, weighing 2 to 4 kg. Either one could be combined with the resonance cells, or the cells could be in a separate photometer.

INFRARED RADIOMETRY

Infrared radiometry is applicable from the top of the visible cloud deck into the ionosphere, roughly from 60 to 130 km above the solid surface. This region comprises -- by analogy to physical processes in the Earth's atmosphere -- the stratosphere, mesosphere, and lower thermosphere of Venus.

Presently available observations of this part of the atmosphere include:

(1) A set of thermal maps made in the 10 to 12 μm window of a region generally associated with the cloud tops. After careful analysis, these observations suggest very small day-night temperature differences and slightly cooler polar regions. Day-to-day variations of a few degrees may be seen, as well as suggestions of meteorological disturbances. The nearly isothermal conditions over the cloud surface suggest that heat must be transported from day to night side by dynamic processes at this level.

(2) A pair of temperature versus height profiles obtained from measurements of the occultation of Mariner 5 by Venus. These cover the range from well below the cloud tops to about 80 km. Above the clouds the lapse rate is about $3.5^\circ/\text{km}$, considerably below the adiabatic lapse rate, but indicating that the region is a true stratosphere. There are indications of vertical structure, with amplitudes of 10°K , and vertical scales of 5 to 10 km. Day-night differences are very small, except near 80 km, where the data become uncertain and show about 10°K .

(3) Observations of planetary scale low-contrast cloud markings in the ultraviolet, which suggest a retrograde atmospheric motion with a period of about 4 days (100 m/sec^{-1} wind velocity). This velocity is confirmed, subject to some variability, by Doppler shifts of spectral lines in the near infrared.

(4) Curve of growth measurements in the near infrared, which suggest that there is an optically thin layer of upper-level cloud, tentatively put at an altitude of 80 to 85 km. It is plausible, but not established, that these clouds are the same as the UV clouds referred to above. A high extension of the cloud or haze is also inferred from transits of Venus over the Sun.

These observations provide only an initial and unclear picture of the upper atmosphere of Venus. Several specific questions can be formulated to increase the detail of present knowledge, and begin to answer questions about the mechanism. Among these are:

- What is the vertical distribution of particulate matter in the Venus atmosphere? Is there a sharp cloud top, a series of layers, or a scale height fall-off? What are their optical properties in the solar and infrared parts of the spectrum? What is their contribution to the local heat budget?
- What is the nature of, and drive for, the 4-day rotation?
- What is the size and vertical variation of the day-night temperature difference, and what is the nature of the motions responsible for heat transport from day to night side?

- What is the nature and importance of the small-scale motions in the atmosphere?
- How do the pressure and temperature at the cloud top or at some opacity level in the haze vary in space and time over the planet?
- How much water vapor, if any, is present above the clouds?

The measurement requirements may be briefly summarized. Absolute accuracy requirements are not extremely high; a few degrees would be sufficient. Precision, or the ability to determine temperature differences, is much more important, and 1 to 2° is required. The ability to resolve at least two scale heights in the vertical, and preferably one, is also required to see small-scale structure, and resolve the region of solar energy deposition. Frequent measurements are also required to see temporal variations.

A powerful method of obtaining temperature and constituent information about a planetary atmosphere is by inverting measurements of the infrared radiation it emits. For sounding the upper atmosphere of Venus, scanning the planet's limb in the infrared could be an efficient method of measurement. Downwards observation is also feasible.

A Venus instrument might have four spectral channels, as follows:

(1 and 2) Two channels in the 15- μ m band of CO₂ to obtain temperature as a function of pressure. The primary purpose would be to obtain measurements for high resolution retrieval to 115 km or higher. In addition, they would yield mean temperatures for two thick layers peaked at 75 and 85 km.

(3) One channel in the 20- to 40- μ m band to measure water vapor emission at the limb, where it may be optically thick; to locate thin cloud layers at the limb; to map cloud temperature and morphology across the disc (viewing downward, the water vapor is optically thin); to allow, from cloud temperature or position, its pressure to be determined from the T(p) solution.

(4) One channel in the visible or near IR band to detect thin cloud (limb-scanning method), and to measure the fine scale of reflectivity variations over the disc.

For limb scanning, optics with a 20-cm aperture would be desirable. Another proposal, depending mostly on downward observation, suggests a 5-cm aperture and 3 additional channels, one using a CO₂ pressure-modulated cell for sensitivity to high altitudes. Either version is estimated to weigh 5 kg.

RADAR ALTIMETRY

The scientific objectives of a backscatter radar study of a planetary surface derive from the analysis of echo delay, intensity and polarization measurements. Relative surface heights (topography) may be determined by a series of measurements of echo delays from resolved surface elements; if these span a

sufficient portion of the planetary surface, the mean radius and oblateness may also be obtained. Small-scale topography is useful in locating and identifying surface features -- for example, impact craters, mountains, slip-faults, river valleys, oceans and lava flows. Measurements of oblateness and other large-scale height variations, when combined with observations of the planet's gravitational field, yield estimates of the degree to which the surface is in isostatic equilibrium.

The intensity of the echo and its polarization -- and the way these vary with wavelength and angle of incidence to the surface -- are intimately related to the electrical and geometrical properties of the surface and immediate subsurface. From the dielectric constant of a material (usually the major determinant of electrical reflective properties), one can place useful limits on its composition and mechanical strength. From the geometrical properties, one may deduce the inclination of coherently reflecting surface undulations as well as the amount of wavelength-sized roughness.

Earth-based planetary radar systems have developed considerable capability in these areas. However, orbital radar altimetry offers the possibility of extending these data into regions inaccessible to suitable observation from Earth, particularly into high latitudes and the planetary polar regions. Radar observations take on particular significance for Venus since the dense and opaque atmosphere of that planet precludes any other means of remotely mapping its surface characteristics.

The radar system listed in the model payload is a basic S-band system (λ between 10 and 15 cm) designed to view only the quasi-specular echo from near the sub-orbital point using same-sense linear transmitted and received polarizations. (Possible add-on modifications would permit: (1) circularly-polarized transmissions for enhancing the value of bistatic radar observations from Earth; (2) dual-polarization reception for studying the diffuse as well as quasi-specular scattering; and (3) an X-band system operating in parallel with the basic S-band system.)

The basic system would have a radar antenna, rotating with the spinning spacecraft, whose angular beamwidth in the direction of spin would be as broad as possible commensurate with a gain of at least 15 dB (for linear polarization, the aperture asymmetry is unimportant). Consider, for example, a beamwidth of $60^\circ \times 20^\circ$. The antenna could be programmed to move in the plane containing the rotational axis so that the antenna would view the surface immediately beneath the spacecraft for some portion of each rotation. The above beamwidths would permit observations for about one-sixth of each rotation (about 2 sec at a spin rate of 5 rpm). For an orbital velocity of 10 km/sec near periape, the spacecraft will move horizontally about 120 km per rotation, with radar observations possible along 20 km of this path.

A phase-coded transmission is desirable. The length of the transmission is limited by the closest planned approach to the surface. A minimum approach of 150 km corresponds to a transmission length of 1 ms. The minimum interval between transmissions (IPP) is set by the maximum unambiguous height required. A height of 1500 km corresponds to an IPP of 10 ms. Thus the radar will have a short-term duty factor of 10 percent. Since the radar will presumably be turned on only during one-sixth of each rotation, the actual periape duty factor will be only about 1.6 percent.

At a nominal height of 400 km above a spherical surface, the lateral (cross-track) resolution would be 10 km for a standard code subinterval or baud length of 1 μ s. The frequency resolution associated with (coherently) decoding the 1-ms transmission code length limits the surface resolution in the direction of the track to about 2.5 km. Resolution in altitude is 150 m, but the accuracy of a given measurement will usually be better than 10 m, depending on the signal strength and the nature of the resolved surface.

Echoes from successive transmission periods are summed incoherently over a time interval determined by the motion of the spacecraft over the resolved surface. In the present example, the time to move 2.5 km is about 0.25 sec, corresponding to 25 IPP's. Thus there would be about 8 separate observations available for each spacecraft rotation, or 40 per minute on the average during periape passage (more per minute at lower altitudes, fewer at higher). Some 500 to 700 altimeter observations may thus be expected per orbit, with about 150 bits of information storage required per observation using the basic proposed system.

An output power of 10 w is assumed available for the 1-ms coded transmission; thus the equivalent peak power after decoding is 10 kw referred to the 1- μ s equivalent pulse (baud) length. It is assumed that the hot planetary surface would add about 500°K to an intrinsic receiver noise temperature of 500°K, for a total of 1000°K. The above system parameters would yield a signal-to-noise ratio of 6700 at 200 km, 800 at 400 km and 47 at 1000 km, assuming radar cross section data typical of Earth-based radar observations.

Placed in a 24-hr polar orbit around Venus, and operated during each periape passage, this basic radar altimeter system would obtain an essentially complete picture of the surface scattering and topography within about 500 km of the pole after 243 days of operation. In addition, it would yield a net of observations between the pole and the equator of extremely high accuracy, which could be referred to Earth-based topographic observations near the equator, and to Earth-based scattering maps over much of the surface.

RADIO OCCULTATION MEASUREMENTS

The S-band radio occultation experiment carried out at Venus by Mariner 5 in 1967 was the first source of information on the structure of the ionosphere and thermal profile of the middle atmosphere of Venus. Since Mariner 5 was a fly-by mission, such measurements could be made only at two points on Venus, one on the nightside of the planet at the time of entry of the spacecraft into occultation, and the other on the dayside corresponding to the exit of the spacecraft from occultation. The technique of deriving the electron profiles and neutral atmospheric density distribution from the precise tracking data at S-band is now well established and extensively documented. In addition to Venus, this experiment has been successfully carried out at Mars by Mariners 4, 6, 7, and 9.

An Orbiter is the most suitable mission for this experiment because it provides frequent repetition of occultations. For low inclination orbits, two occultations occur per revolution. Above some limiting inclination, depending on orbit shape, occultations are not observed for parts of the mission. In any case, full longitudinal coverage is achieved and two bands, roughly parallel to the equator, could be scanned during mission lifetime. An excellent example is

Mariner 9, which has now provided several hundred density profiles in the atmosphere of Mars over a large range of latitudes and longitudes. For a medium or high inclination Venus Orbiter, occultation sequences are limited to special periods of about two months' duration, yielding less longitudinal but more latitudinal coverage.

In addition to ionized and neutral density profiles, the radio occultation experiment can acquire extremely important information on the vertical structure of clouds on Venus. The occultation experiment on Mariner 5 has given some preliminary indication of the existence of absorbing layers in the middle atmosphere of Venus. The Probe mission of the Pioneer Venus program will characterize the nature of these low-level clouds and their structure at four different points on the planet. A radio occultation experiment on the Orbiter mission will considerably enhance the global coverage, both in space and time.

In order to realize the full potential of a radio occultation experiment in Venus orbit, the following requirements must be met:

- (1) The Orbiter high-gain antenna must be able to follow the direction of the radio beam when it is refracted in the atmosphere of Venus.
- (2) A second frequency coherent with the S-band frequency must be provided on the downlink.

The first requirement arises from the fact that a large amount of refractive bending (up to 17°) occurs in the dense lower atmosphere of Venus, and in order to obtain significant information on the nature of the lower clouds of Venus and their change with time, one must be able to observe both the phase and the amplitude of signals of both frequencies to establish the dispersive absorption effect. This can only be accomplished if the pointing direction of the antenna can be programmed to follow the expected refracted direction of the radio beam. Methods for doing this are under study. This can be accomplished in two ways:

- (1) By providing a mechanically despun two-axis steerable antenna if the spin axis direction of the spacecraft is perpendicular to the ecliptic plane.
- (2) If the two-axis steerability of the antenna is to be avoided, or if the spacecraft spin axis lies in the plane of the ecliptic, the spin axis of the spacecraft should be used to readjust the spin axis direction according to a preset program. Without this maneuver, penetration depth as well as latitudinal and longitudinal coverage would deteriorate significantly, especially at X-band but also at S-band.

In addition to automatically calibrating out effects of changing abundances of interplanetary electrons (which is much more important for a Venus Orbiter than it is for a Mars orbiter), the main advantage of having two coherent frequencies on a downlink lies in the ability to measure the frequency-dependent characteristics (e.g., absorption) in the dense lower clouds of Venus at two frequencies, thereby inferring their behavior with latitude, solar illumination angle, and time -- especially in the presence of composition data supplied by the Pioneer Venus entry capsules.

Improved sensitivity to weak ionospheric layers would be provided by an L-band downlink; however, at the time of the Venus Pioneer Orbiter mission, the Deep Space Network (DSN) stations would be instrumented to receive only X-band. Perhaps other tracking facilities may be brought to bear on L-band transmission.

GRAVITATIONAL MEASUREMENTS

There is a basic conflict between in situ measurements of the upper atmosphere and the gravitational experiments. In situ measurements require low periapsis and an active process requiring orbital maneuvers to maintain low periapsis. The gravitational experiments require periapsis high enough to avoid atmospheric drag effects and long periods of tracking data, uninterrupted by orbital maneuvers and active attitude control. In addition, gravitational experiments would profit from smaller eccentricity (the smaller the better), maximum orbital tracking coverage, maximum accuracy of tracking data, and -- within the constraint of long uninterrupted sequences of data -- several distinct orbits.

There is no need to reemphasize the interest in determination of the gravity field of Venus as well as of its geometrical shape. One needs merely to recall the interest of this objective in relation to the similarity between Venus and the Earth as planets. The origin and evolution of the inner solar system may be strongly related to the actual differentiation of these two planets insofar as rotation rate, figure, atmosphere, etc., are concerned. A possible interaction between atmosphere dynamics and the solid planets may be fundamental in explaining the unique situation of the spin-orbital coupling with the Earth. Knowledge of the ellipticity of the equator and, more generally, the inertia ellipsoid, are essential parameters to be determined.

Since the primary mission objectives do not include gravitational experiments, it is recommended in the strongest terms that the mission be extended beyond the nominal 243 days' duration for the main purpose of conducting the gravitational experiments.

The following conditions should be fulfilled:

(1) Availability of S- and X-band communication links for extensive tracking before and after Sun occultation from the 225th to the 280th day (around superior conjunction).

(2) No active control of the orbit, and no attitude control, thus allowing the periapsis to rise naturally above 500 km, and stabilizing the spacecraft by increasing the spin rate.

(3) Frequent high accuracy tracking (accuracy better than 10 m range, 3 mm/sec range rate); at least 20 minutes of tracking data every 2 hours for 2 days every week are considered reasonable.

(4) Extended mission of at least one sidereal rotation period of the planet (243 days).

The main goal is to have a long period during which the spacecraft is moving in a natural motion under the influence of gravitational forces and environmental forces, with the reasonable assumption that the nongravitational perturbations can be modeled accurately.

SUPPORTING STUDIES

The candidate payload was carefully constructed to consist of a self-sufficient experiments package to address the first-order scientific questions concerning Venus that are peculiar to the Orbiter. This has been accomplished within spacecraft constraints, to first-order. There are, however, possible supporting studies which would enhance the scientific output. For example, rocket- or Earth-orbiting satellite-borne solar EUV and soft X-ray spectrometers would provide knowledge of the photo-excitation, dissociation and ionization levels impinging on the Venus upper atmosphere. Such spectrometers are to be flown aboard the Atmospheric Explorer satellites; some thought might be given to ensuring their availability for measurement during the Venus Orbiter mission. As another example, there are various Earth-based, airborne, rocket-borne and satellite-borne techniques, particularly in the infrared, that have been used for planetary observations -- and no doubt will be used again -- within the Pioneer Venus time-frame. If their use could be synchronized with the Pioneer Venus Orbiter, the latter could well provide very useful calibration data to the near-Earth observations.

CONCLUSIONS

Enthusiastic support for a joint NASA/ESRO Venus Orbiter mission was clearly evident among the Joint Working Group scientists. Reasons for this enthusiasm included: the number of first-order questions about Venus that can be answered by the candidate payload; the obvious cost-effectiveness of the mission, enhanced by the sharing of resources between NASA and ESRO; and the major opportunity afforded by the Pioneer Venus effort to the European space community to enter the field of planetary exploration.